High-Q submicron-diameter quantum-dot microcavity pillars for cavity QED experiments

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SC-1: Semiconductor quantum devices and mesoscopic physic

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Time: Monday 14:00–16:00 Location: Salle du Conseil

SC-1.1 MON 14:00 Salle du Conseil

High-Q submicron-diameter quantum-dot - microcavity pillars for cavity QED experiments — •N. Gregersen[1], M. Lermer[2], F. Dunzer[2], S. Reitzenstein[2], S. Höfling[2], J. Mørk[1], L. Worschech[2], M. Kamp[2], and A. Forchel[2] — [1]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads, Building 343, DK-2800 Kongens Lyngby, Denmark — [2]Technische Physik, Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

The semiconductor quantum dot - microcavity pillar system represents an attractive platform for studying fundamental light-matter interaction as well as for demonstrating novel quantum devices, ultra-low threshold lasers and sub-ps optical switching. In this work we present a novel tapered GaAs/AlAs micropillar design where Bloch-wave engineering is employed to significally enhance the cavity mode confinement in the submicron diameter regime. We demonstrate a record-high vacuum Rabi splitting of 85 μeV of the strong coupling for pillars incorporating quantum dots with modest oscillator strength $f \approx 10$.

It is well-known that light-matter interaction depends on the photonic environment, and thus proper engineering of the optical mode in microcavity systems is central to obtaining the desired functionality. In the strong coupling regime, the visibility of the Rabi splitting is described by the light-matter coupling constant g proportional to $Q/\sqrt{V}$, where Q is the quality factor and V is the mode volume. A high Q and a low V are thus desirable.

The mode volume V can be minimized by reducing the pillar diameter. However, for the standard micropillar design, the poor mode matching between the cavity mode and the DBR Bloch mode limits the Q to about 2000. [1] In our optimized design we have replaced the standard λ-spacer with a 3 segment tapered region. The layer thicknesses of these GaAs/AlAs segments are gradually reduced towards the center, effectively detuning the bandgap relative to that of the DBRs and allowing for a single localized mode inside the cavity. The fundamental Bloch mode experiences an adiabatic transition, leading to an improved mode matching and a reduced coupling to propagating Bloch modes in the DBRs. The central GaAs layer incorporating quantum dots is only 60 nm thick corresponding to $\approx \lambda/5$, and regular cavity concepts are thus insufficient to explain the localization of the cavity mode, demonstrating the necessity of Bloch-wave formalism in the analysis of the design.

We compare our adiabatic design to a reference incorporating a λ-spacer. A theoretical improvement of Q of two orders of magnitude and an experimentally measured improvement of ≈ 5, limited by fabrication imperfections, are obtained. Thus our novel approach allows us to demonstrate remarkably high quality factors exceeding 10,000 for MP cavities with diameters below 1 μm. [2]

Whereas previous studies of strong coupling in micropillars relied on quantum dots with high oscillator strengths $f > 50$, our advanced design allows for the observation of strong coupling for submicron diameter quantum dot-pillars with standard $f \approx 10$ oscillator strength. A quality factor of 13600 and a vacuum Rabi splitting of 85 μeV are observed for a small mode volume micropillar with a diameter of 850 nm.

[1] P. Lalanne, J. P. Hugonin and J. M. Gérard, Appl. Phys. Lett. 84, 4726 (2004).

[2] M. Lermer, N. Gregersen, F. Dunzer, S. Reitzenstein, S. Höflling, J. Mørk, L. Worschech, M. Kamp and A. Forchel, accepted for publication in Phys. Rev. Lett.

SC-1.2 MON 14:15 Salle du Conseil

Coupled microdisk-ring cavity for quantum-dot laser structure — S.-Y. Tsai, T.-E. Tzeng, T.-Y. Huang, and •T.-S. Lay — Department of Photonics, National Sun Yat-Sen University, Kaohsiung 804, Taiwan

We report the fabrication and optical properties for a coupled microdisk-ring laser structure of InGaAs quantum dots. The sample epi-structure is grown on (100) GaAs substrate by molecular beam epitaxy (MBE). The active layer contains six layers of self-assembled InGaAs quantum dots. The emission wavelength is 1200 nm for the InGaAs quantum dots. Beneath the active layer, a distributed Bragg reflector (DBR) consisting of 23.5 pair of GaAs/AlAs is grown to reflect the emitted photons from the active layer, and enhance the optical confinement in the active layer. The coupled micro-disk cavity is fabricated by electron beam lithography and dry etching process. The diameter of the microdisk is 3 um, and a ring of width = 250 nm skirts around the microdisk with an air gap = 100 nm. The width for the ring is chosen to maintain a fundamental lateral optical mode. The etching depth is 1.58 um for the coupled cavity. The finished device shows a smooth surface and a sharp-etched air gap confirmed by scanning electron microscope (SEM). The optical characteristics for the coupled microdisk-ring quantum-dot laser structure are measured by micro-PL. The spectrum shows eminent peaks related to the whispering gallery modes (WGMs) for the micro-cavity. The WGMs are identified by two dimensional finite-difference time-domain (FDTD) simulation. In addition to the fundamental modes for the microdisk and ring, coupled microdisk-ring modes are observed.

SC-1.3 MON 14:30 Salle du Conseil

Optical wavelength shifting using resonant non-linearities in THz quantum cascade lasers — •P. Cavalié[1], J. Madéo[1], J. Freeman[1], J. Maysonnave[1], K. Maussang[1], H. Beere[2], D. Ritchie[2], C. Sirtori[3], J. Tignon[1], and S. Dhillon[1] — [1]Laboratoire Pierre Aigrain, Ecole Normale Supérieure, UMR 8551 CNRS, University P. et M. Curie, University D. Diderot, 24 rue Lhomond, 75005 Paris, France — [2]Semiconductor Physics Group, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK — [3]Matériaux et Phénomènes Quantiques, Université Denis Diderot - Paris 7, UMR 7162 CNRS, 75013 Paris, France

Wavelength division multiplexing is used in optical fiber networks and wavelength shifting is essential for data routing. Optoelectronic devices are currently used to perform wavelength shifting where an optical signal is converted into an electrical signal and then back to an optical signal. This scheme presents a large disadvantage of a speed bottleneck. To overcome this problem, all-optical networks have been proposed as an effective solution. Non-linear processes in semiconductor devices have the potential to fill this technological gap where two wavelengths in a material are mixed to generate the sum or difference frequency, shifting the original wavelength. Non-linear wave mixing between a near-infrared probe in presence of an intense terahertz (THz) beam in quantum wells systems has been already demonstrated [1]. However, the THz radiation was provided by a Free Electron Laser (FEL) that strongly limits its relevance to applications. In this work, we demonstrate intracavity frequency mixing using the resonant interband nonlinearities of a compact and practical device - the quantum cascade laser (QCL) [2].

The THz QCL laser transition E_{QCL} occurs between confined subbands within quantum wells of the conduction band (intersubband transitions). A near-infrared beam (NIR) E_{NIR} is coupled into the QCL cavity that is at the same energy as the latter's effective bandgap. The geometry leads to a resonant enhancement of the second order non-linearity permitting difference frequency generation [3]. As a result, E_{NIR}-E_{QCL} is generated via a virtual state below the bandgap. The sample used was a GaAs based 2.8THz bound-to-continuum QCL. As the QCL is taken above laser threshold, the difference frequency is observed for pump excitations over a range of few meV (1.523eV< E_{NIR} <1.534eV). The generated beam is separated from the pump E_{NIR} by exactly the photon energy of the THz QCL (E_{QCL} = 11.5meV) and below the bandgap of the material. A resonant behaviour is found in the conversion efficiency with a maximum conversion efficiency of 0.13 % observed for pump energies of 1.527eV.

Photoluminescence (PL) of the QCL was used to identify the states involved in the nonlinear process. The observed resonances in conversion efficiency match transitions revealed with the PL which correspond to interband transitions between the lowest lying hole states and the electronic states of the QCL miniband. This shows that the pump is resonant with real transitions that enhance the non-linearity. The estimated $\chi^{(2)}$ from the efficiency measurements and taking into account the optical losses for the pump is found to be 10^4 pm/V, roughly in agreement with the typical values of interband non-linearities (10^2-10^4) [4].

To conclude, we have demonstrated optical wavelength conversion by using the resonant interband non-linearities within a THz QCL with efficiencies that are comparable to those from FELs[1]. The perspectives of this work are wide ranging. As well as engineering of the non-linearities by optimisation of the wavefunction overlap, interband resonances could be directly tuned to the telecom window using mid-infrared InGaAs-based QCLs. These operate at room temperature and would permit wavelength shifting between different telecommunication bands.

[1] S. G. Carter et al., "Terahertz electro-optic wavelength conversion in GaAs quantum wells: Improved efficiency and room-temperature operation ", App. Phys. Lett. 84, 840-843, 2004

[2] R. Köhler et al., "Terahertz semiconductor-heterostrcuture laser ", Nature 417, 156-159, 2002

[3] V. Ciulin et al., "Terahertz optical mixing in biased GaAs single quantum wells ", Phys. Rev. B. 70, 115312, 2004

[4] E. Garmire, A. Kost et J. Khurgin. " Nonlinear optics in semiconductors II ". Academic Press, 1999. (pages 112, 120, 149 et 156.)

SC-1.4 MON 14:45 Salle du Conseil

Multiphoton excitation of quantum dot in presence of Time Dependent fields for bioimaging. — •P. Jha, S. Lahon, and M. mohan — Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India.

Recently, multiphoton processes in nano-structures have attracted much attention for their promising applications, especially in growing field of bioimaging [1]. Here we investigate the optical response of Quantum Disc (QD) in the presence of laser and a static magnetic field. In this work we study the multiphoton intraband transition in the stable QD in laser aiming for making ultra sensitive THz bioimaging and photo detector devices [2]. Floquet theory is employed to solve the equation of motion for laser driven intraband transitions between the states of the conduction band. Floquet theory relates the solution of Schrödinger equation involving a periodic Hamiltonian to the solution of another equation with a time independent Hamiltonian represented by an infinite